Lightweight Aluminum mirrors using foam core sandwich construction

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The possible use of all aluminum mirrors made from thin faceplates supported by aluminum foam is explored from an optomechanical design and fabrication perspective. Foam mirrors can be relatively cheaply and easily made using conventional foam fabrication and diamond turning; such a mirror recently flew for the first time on the Stardust mission. The proposed structural concept is highly weight efficient and should not be prone to quilting. The weight and structural stability of such mirrors is presented, along with plans underway at GSFC for developing this concept.

Outline

- Introduction
- Motivation for foam mirrors
- Fabrication aspects
- Basics of Al foams and foam sandwich mirrors
- Methods of analyzing foam mirror designs
  - simple minded scaling with aperture using conventional rules
  - optimal foam mirror design
- Results of analysis for Al foam mirrors
- Potential for SiC foam mirrors
- Conclusions for large space based telescopes
- Research planned at GSFC

Introduction

- Foam structures are highly efficient. Examples from nature include wood (e.g. cork, balsa, etc) and bone
- Foam mirrors can be thought of as the end-evolution point of core-sandwich type mirrors for maximum specific stiffness
- Al foam is readily available commercially[1] with faceplates brazed on and ready for diamond turning mirror fabrication
- At GSFC, we have developed a process to directly polish Al mirrors

- So this presentation explores the potential for all-aluminum foam core mirrors for large ultralightweight optics.

Introduction

- Advantages of Aluminum as a mirror material:
  - Relatively lightweight
  - Highly isotropic
  - High thermal conductivity
  - Cheap (significant for ~ 700 m^2 areas of 30m telescopes)
  - Amenable to diamond turning
  - Readily used as a structural material, which allows isothermal systems
- Disadvantages:
  - Relatively low elastic modulus (stiffness)
  - High CTE and thermal distortion
  - Historically has required plating with more polishable coating

Motivation

- Vukobratovich and coworkers[2-4] have shown that sandwich construction mirrors are more weight efficient than other designs, including single and double arch, solid, and open-back designs. The problem of quilting can be overcome by using a high pore density foam, such as ERG's Duocel Al foam, available in pore densities up to 40 pores per inch (ppi).
- Such Al mirrors have the potential to be very light for a given stiffness, as well as being amenable to cyrogenic applications based on all Al construction.
- In addition, such mirrors should be dramatically cheaper to build than competing materials such as Be or SiC monolithic panels.

Fabrication aspects

- At GSFC a method of directly polishing Al mirrors has been

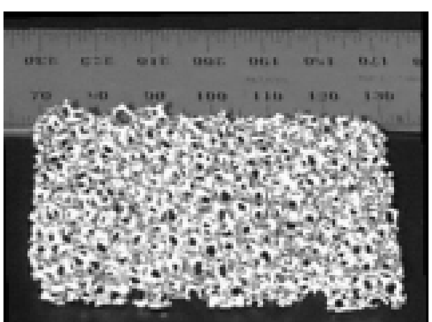
ERG and other foam vendors can readily produce foams useable as structural backing for sandwich mirrors. The Stardust mission recently flew an Al foam fold mirror.

Foam basics

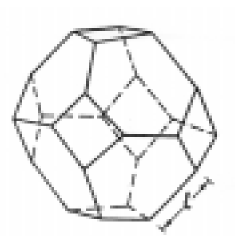
- Parameters that can be independently varied include the relative density ρ_r and the pore density.
- The materials properties of ideal tetrakaidecahedral open cell foams are[5] (recent measurements[6] confirm this for ERG's Duocel foam):
  - Elastic modulus: $$E_{foam} / E_{solid} = \rho_r^2$$
  - Shear modulus: $$G_{foam} = C_g \rho_r^2 E_{solid}$$
    - C_g=3/8 for isotropic foams
  - Thermal conductivity: $$C_{foam} / C_{solid} = \rho_r (0.33)$$
- Relative densities down to about 0.03 are available.

Foam basics, continued

- Foam sandwiches are fully annealed as part of the fabrication cycle, thus parts are free of residual stresses and should be ready for cryogenic use



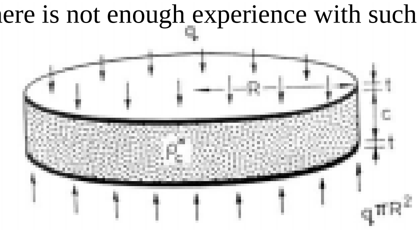
Al Foam sample, 10 ppi, ~10% relative density



Tetrakaidecahedral structure
(Adapted from Ref. 5, p. 27)

Foam basics, continued

- The mechanical properties of foam by itself are clearly inferior to conventional materials. The elastic modulus, shearing modulus, and thermal conductivity are lower than for solids. However, in a sandwich configuration, such as is shown below, the variability of the materials properties suggested by the scaling laws above allows significant lightweighting for a given level of performance.
- These considerations also demonstrate the complications inherent in designing foam mirrors. This paper can only show the long-term potential, as there is not enough experience with such mirrors yet.



Foam basics, continued

- ERG's "Rules of thumb" for foam mirror construction[7] include:
  - Make facesheet at least as thick as 1/2 pore spacing (rule#1)
  - Divide weight of mirror equally between core and 2 facesheets (front and back)
  - Maintain a conventional 6:1 aspect ratio
- Implications of using these rules:
  - For a given relative density, a small pore spacing allows thinner facesheets and a lighter mirror
  - Mirror weight will scale as cube of diameter and areal density linearly with diameter
  - Example (aggressive) design: 1 meter diameter, 3% relative density:
    - 2.43 mm facesheet thickness, foam and faceplates each weigh 11.1 kg, shear panel weighs 3.7 kg, areal density is 33 kg/m^2, weight is 6.8% of equivalent 6:1 aspect ratio solid Al mirror.

Optimal foam mirror analysis

- Analysis of minimum weight cylindrical foam panels (without shear panels) for a specific stiffness has been analyzed by Desmetz and Gibson[8]. They calculate the flexural rigidity and shear rigidity as a function of the three design parameters c, t, and ρ_r. The approach taken here is to examine the deflection due to self-weight bending (shear will be alleviated by the shear panels, but they are not modeled) for which the general equation is[2]:

$$\delta = C\frac{qR^4}{D}$$

- Flexural rigidities for solid and foam are:

$$D_{solid} = \frac{E_f h^3}{12(1-\upsilon^2)}$$

$$D_{foam} = \frac{E_f}{12(1-\upsilon^2)}\left(t^3 + 6t\left(c+t\right)^2 + \rho_r c^3\right)$$

q=$\square_a$ g load per unit area

$\square_a$ weight per unit area, areal density

ρ_r relative density

c core thickness

t facesheet thickness

υ Poisson's ratio for solid

E Elastic modulus for solid

R plate radius

δ allowed deflection

D flexural rigidity

Optimal foam mirror analysis, continued

- These equations were used to determine the self-weight deflection for each design; these were then compared to the self-weight deflections of a 6:1 aspect ratio solid mirror. The goal is to minimize areal density for the equivalent deflection as a solid mirror.
- Two approaches were considered:
  - 1) As in the original example, set the relative density to the minimum value, maintain a 6:1 overall aspect ratio, and vary c (or t) to minimize weight
  - 2) Divide weight as recommended by Desmetz and Gibson[8] for an ideal foam (1/4 in both faceplates and 3/4 in the core) and vary c (or t) and ρ_r
- Results are (1 meter diameter case):

Constraint used			6:1 aspect ratio		wt divided	
Relative density of core		rho_r	**0.03**	0.02	0.03	0.02
Thickness of core	mm	c	**164.1**	165.0	214.4	214.6
Thickness of faceplate	mm	t	**1.26**	0.84	0.80	0.54
Overall aspect ratio		R/(2t+c)	**6**	6	4.63	4.64
Overall areal density	kg/m^2	rho_a	**20.1**	13.4	21.7	14.5
density ratio to 6:1 solid			**0.045**	0.030	0.048	0.032

Optimal foam mirror analysis, continued

- Points to note from the above analysis:
  - **The length parameters c & t scale with part radius**
  - **The materials properties normalize out - same design independent of material (as long as it is used for both facesheet and core, as desired for CTE matching)**
  - **Areal density will again increase linearly with part radius**
  - **ERG’s rule of thumb for weight division is not borne out by this analysis**
  - **Suggests need for more careful analysis, e.g. FEA**
  - **Facesheets are still quite thin**
    - Not much margin for error in fabrication
- If enough shear rigidity is added by the shear panel, higher aspect ratios than 6:1 will be lighter than shown here, but this requires more sophisticated analysis methods.

Optimal foam mirror analysis, continued

- SiC (and other material) foams are also available. The same comparison was run for SiC foam mirror designs (again 1 m diameter case is shown) but using a 10:1 ratio for the solid mirror:

Constraint used			10:1 aspect ratio	wt divided		
Relative density of core		rho_r	**0.03**	0.02	0.03	0.02
Thickness of core	mm	c	**98.5**	99.0	128.6	128.8
Thickness of faceplate	mm	t	**0.76**	0.50	0.48	0.32
Overall aspect ratio		R/(2t+c)	**10**	10	7.72	7.73
Overall areal density	kg/m^2	rho_a	**14.3**	9.6	15.4	10.3
density ratio to 10:1 solid			**0.045**	0.030	0.048	0.032

Because of the improved materials properties of SiC, the mirrors are much lighter than the equivalent Al design. Unfortunately, the cost and time required to polish SiC facesheets significantly increases costs.

Conclusions for large space telescopes

- Al foam sandwich mirrors represent a potentially cost effective way to fabricate ~1m panels usable without active figure control for room temperature or cryogenic applications in the visible and longer wavelengths.
- 1 meter flat panels achieve ~20 kg/m^2, close to NGST metric of 15 kg/m^2
- SiC foam sandwich mirrors are very attractive as a lighter weight option but fabrication will be much more expensive

Plans for developing foam mirrors at GSFC

- Initiatives underway or proposed at GSFC to exploit the potential of the Al superpolishing and Al foam sandwich mirrors include:
  - DDF to refine superpolishing techniques and to demonstrate on aspheric mirrors
  - Purchasing 15 cm foam sandwich flats to explore diamond turning and polishing aspects
  - Proposal to Cross-cutting technology program to:
    - Establish materials properties of Al and other foams for optical applications (e.g. microcreep, CTE uniformity, etc)
    - demonstrate cryogenic performance of superpolished direct Al mirrors both on conventional and foam sandwich substrates
    - Improve opto-mechanical analysis and design models beyond the basic approach given here
    - Scale up to larger foam mirrors and aspheric shapes.

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Acknowledgements

We would like to acknowledge useful discussions with L. Feinberg, M. Hagopian, B. Leyda, B. W. Bach, and the timely preprints provided by L. Gibson.